A Long Range Plan
for
U.S. High Energy Physics

HEPAP Subpanel
on
Long Range Planning

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HEPAP
January 28, 2002

Subpanel Membership

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Persis Drell - Cornell University
Glennys Farrar - New York University
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George Kalmus - Rutherford Appleton Lab
Rocky Kolb - Fermilab
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William Marciano - Brookhaven Natl Lab
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Abraham Seiden - Univ of Calif, Santa Cruz
Melvyn Shochet - University of Chicago
William Willis - Columbia University
Fred Gilman (Ex-Officio) - Carnegie Mellon
Glen Crawford (Executive Secretary) - DOE

Our report is the result of an extensive one-year process, involving the U.S. and international communities

The Goal of our Subpanel

To Create a Vision for the Field for the Next 20 Years

The questions we posed for ourselves

- **What is our role in society and education?**
- **What is high energy physics?**
- **What are our goals and paths to accomplish them?**
- **How have we been doing?**
- **What do we expect in the near term?**
- **What opportunities do we identify for the longer term?**
- **How do the U.S. and global programs inter-relate?**
- **What are the essential elements of a realistic program aimed at our goals?**
- **How can we set priorities and make the best choices?**
- **How do we prepare for the far future?**

What is our Role in Science, Education and Society?

- **Public education is a responsibility and privilege of our field**
  - **Current program is very successful**
  - **Quarknet**
  - **REU programs**
  - **Lederman Science Center**

Activity on education and outreach should be doubled to ensure a viable, effective and sustainable program.

What is our Role in Science, Education and Society?

- **Connections between science and technology**
  - ***Physics in a New Era*** **(NRC Report)**

    There are now extraordinary opportunities for addressing the great questions surrounding the structure of matter, the unification of fundamental forces, and the nature of the universe. New applications to technology and to the life sciences are emerging with increasing frequency. New links are being forged with other key sciences such as chemistry, geology, and astronomy.

    [There are] new directions branching off from old, with great potential for having a wide impact on science, medicine, national security, and economic growth.

What is our Role in Science, Education and Society?

- **Connections to National Security**
  - *Science, the Endless Frontier* (Vannevar Bush)

    … [W]ithout scientific progress no amount of achievement in other directions can insure our health, prosperity, and security as a nation in the modern world.

  - **U.S. Commission on National Security/21st Century (Hart-Rudman Report)**

"National security rests on the strength of our scientific and technological base. The entire portfolio must be maintained to ensure the health, welfare and security of the nation in years to come."

What is Particle Physics?

The Classic Definition

International Union of Pure and Applied Physics

Commission on Particles and Fields
C11 Commission (1957)

The Mandate for C11:

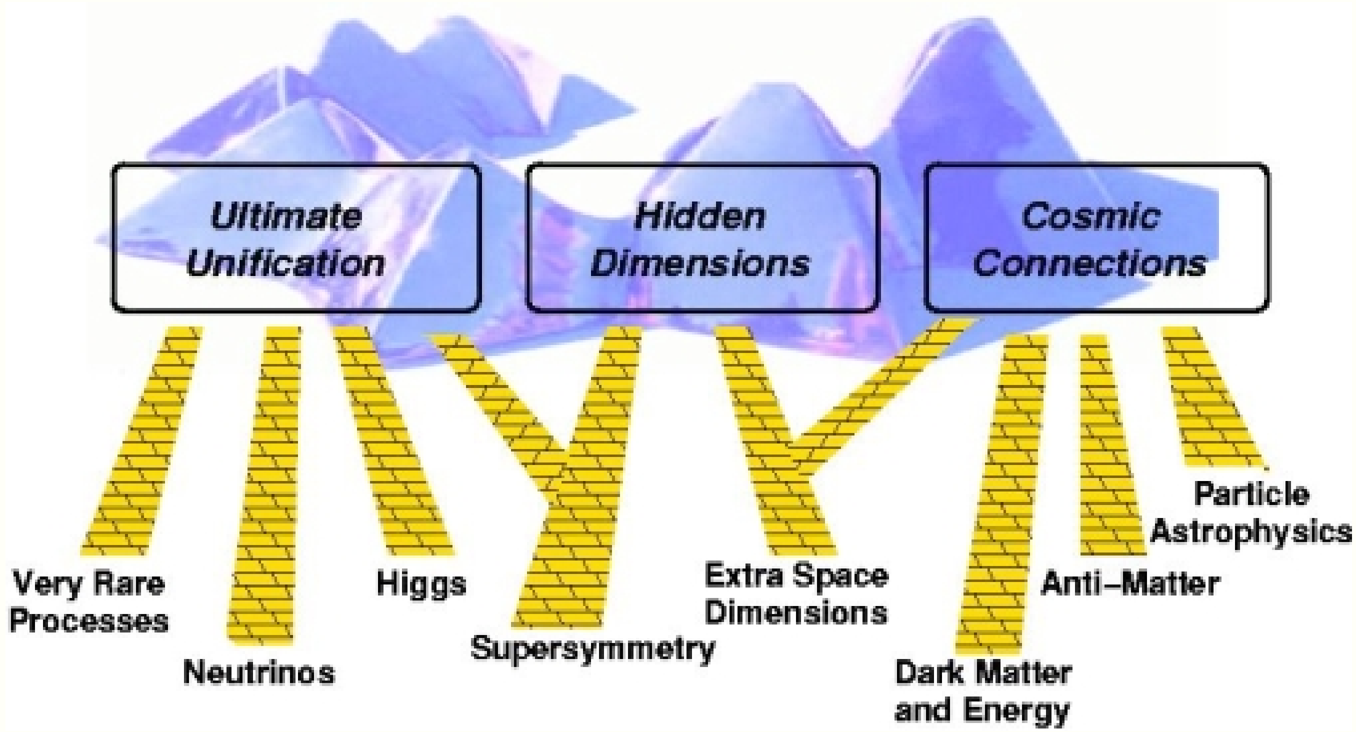
"… the theory and experiment concerned with the nature and properties of the fundamental constituents of matter and the forces acting between these constituents"

We asked ourselves: How WE define our field?

What is Particle Physics?

Our Definition

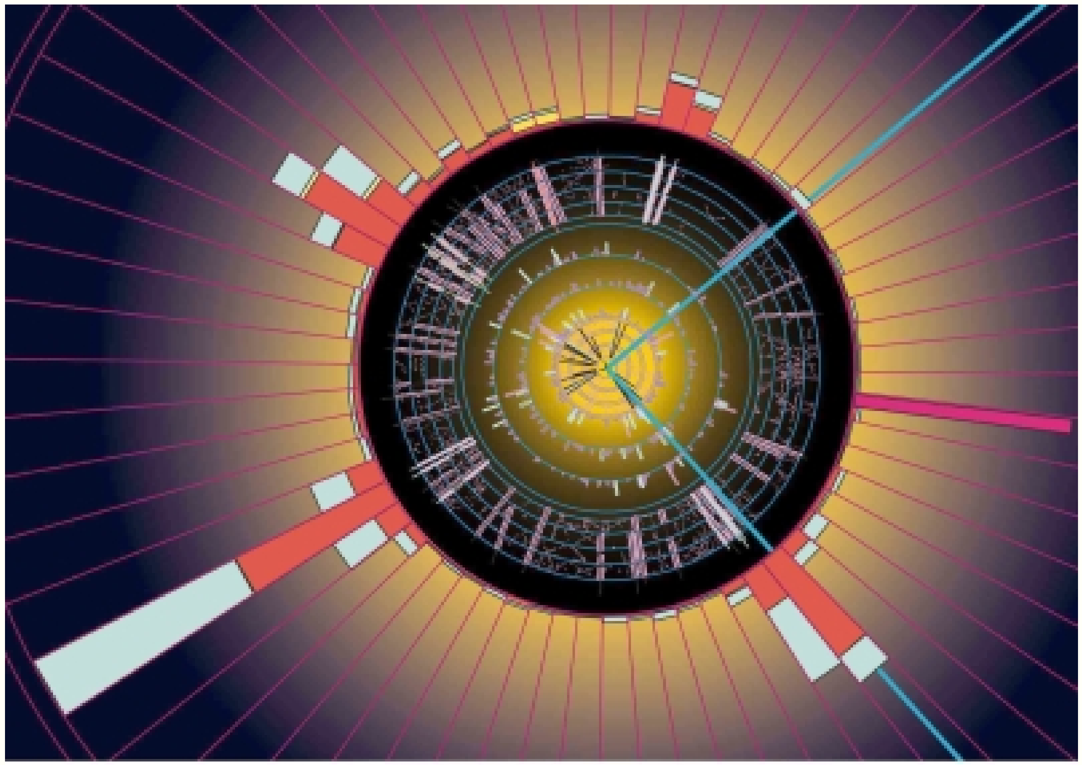
The Science of Matter, Energy, Space and Time



The Paths and Goals of Particle Physics

How Have We Been Doing? Recent Steps

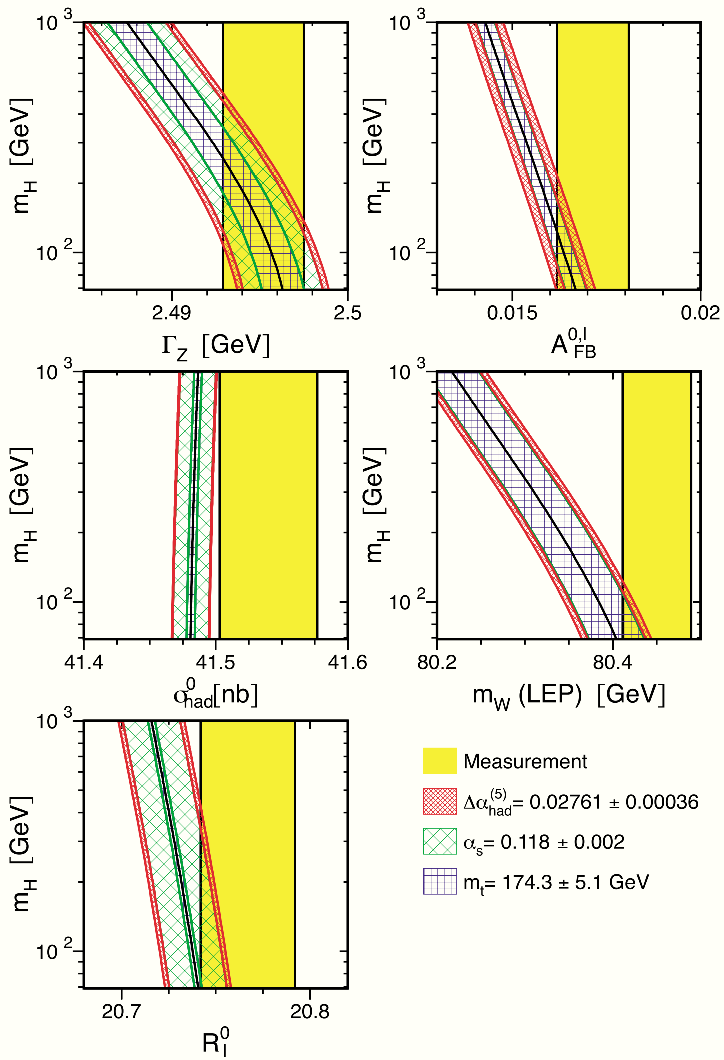
The Last Quark

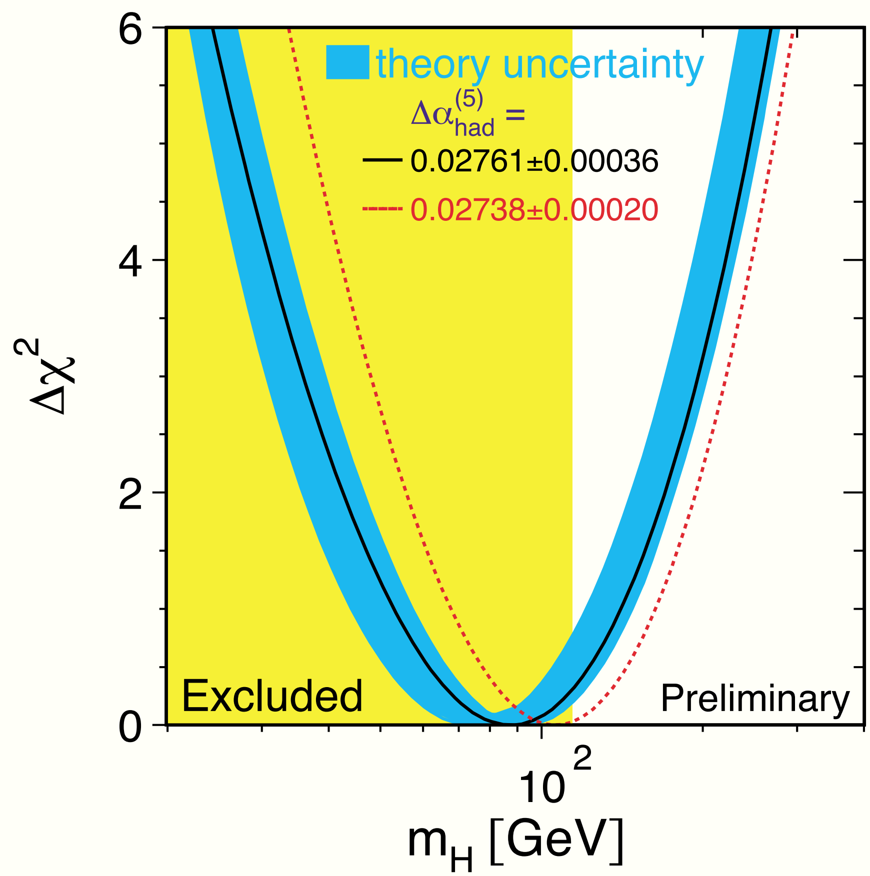


Top Quark Event from Fermilab. The Fermilab Tevatron is the only accelerator able to produce and study the most massive quark.

How Have We Been Doing? Recent Steps

Electroweak Precision Measurements

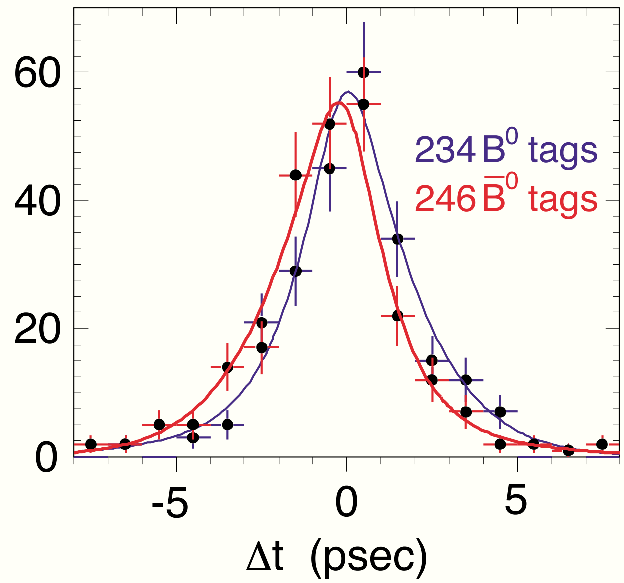




A worldwide effort, centered at CERN.

How Have We Been Doing? Recent Steps

Matter–Antimatter Asymmetry



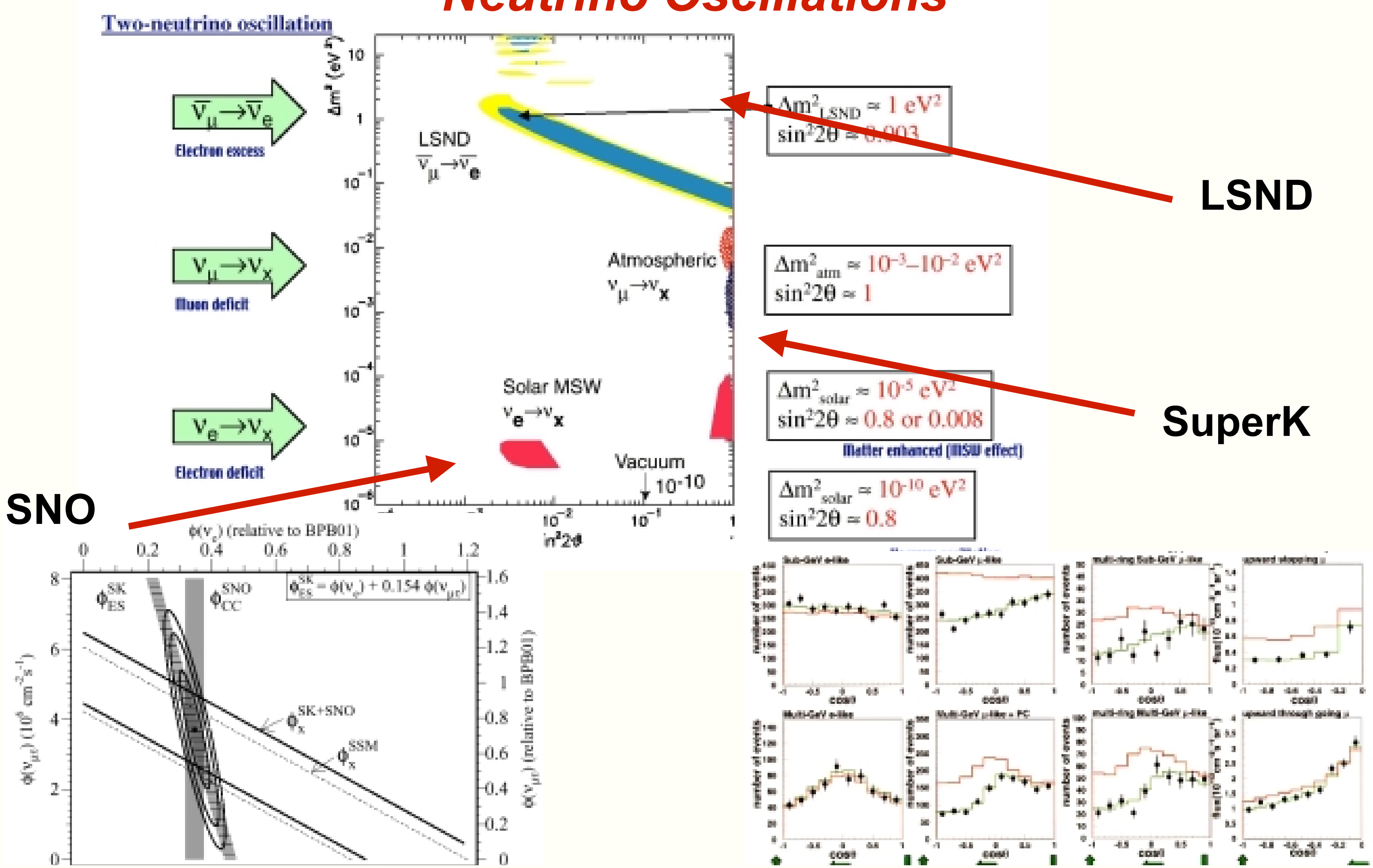
SLAC BaBar Data

KEK BELLE Detector

Anti-matter asymmetry detected at SLAC and KEK.

How Have We Been Doing? Recent Steps

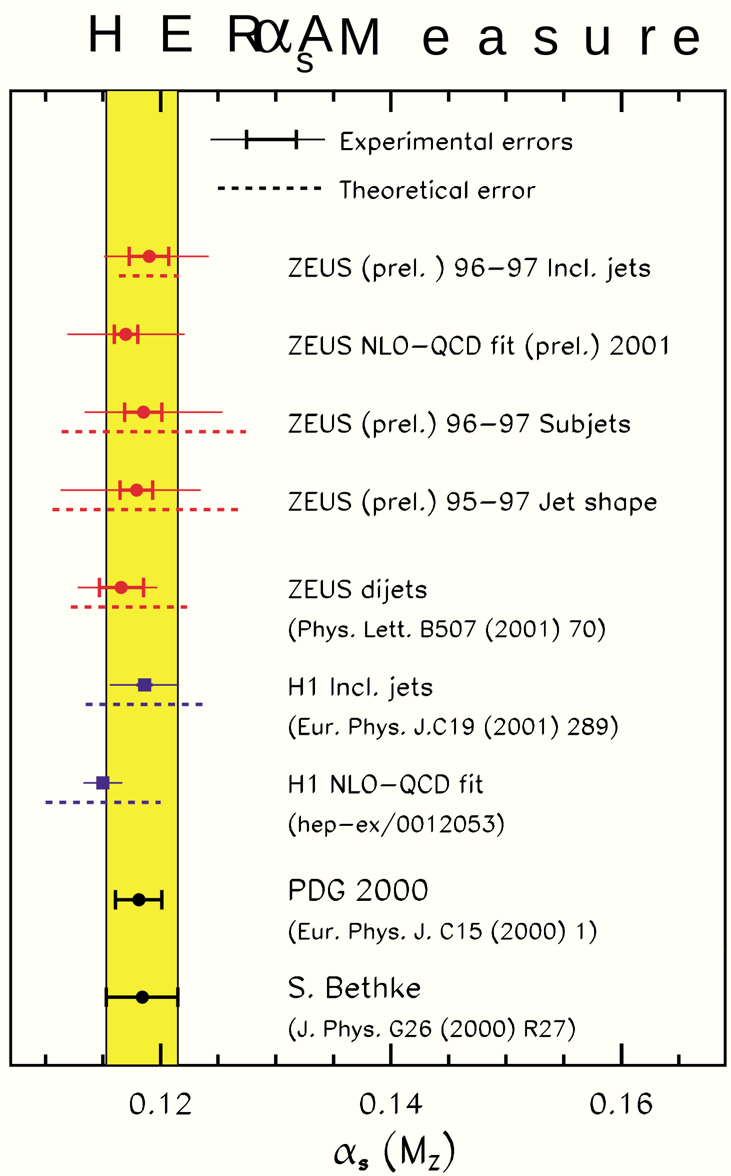
Neutrino Oscillations



Non Accelerator Experiments

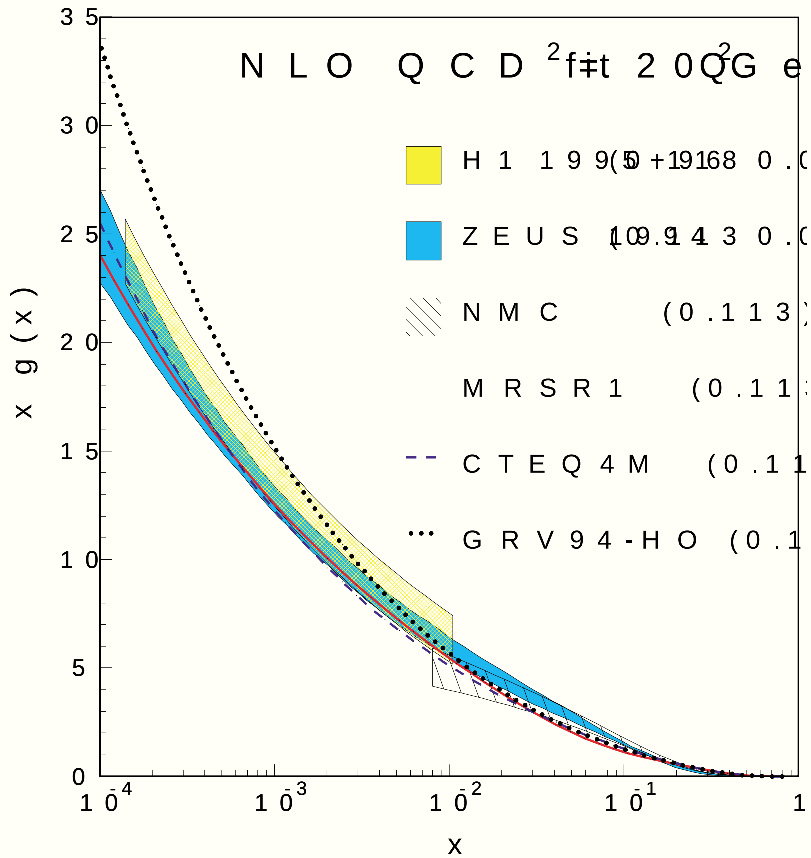
The Next Steps: What to Expect?

Existing and Near Term Program



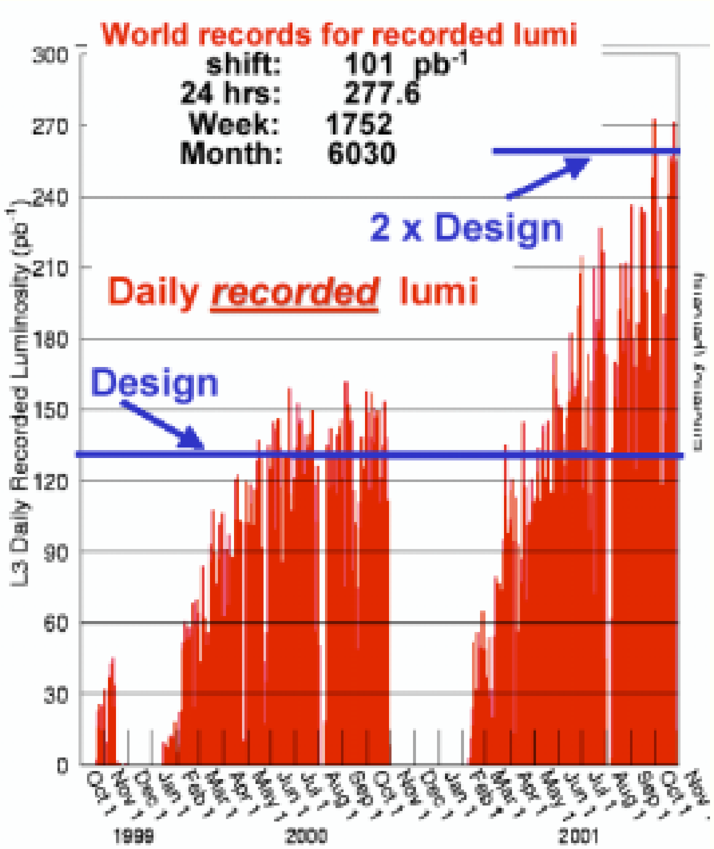
H1 and Zeus

Structure functions, QCD, new physics



The Next Steps: What to Expect

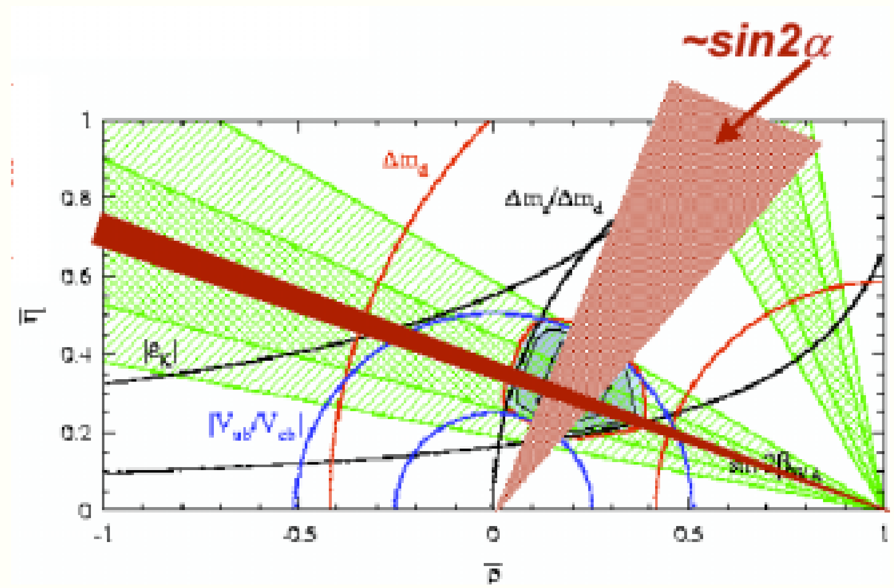
Existing and Near-Term Program

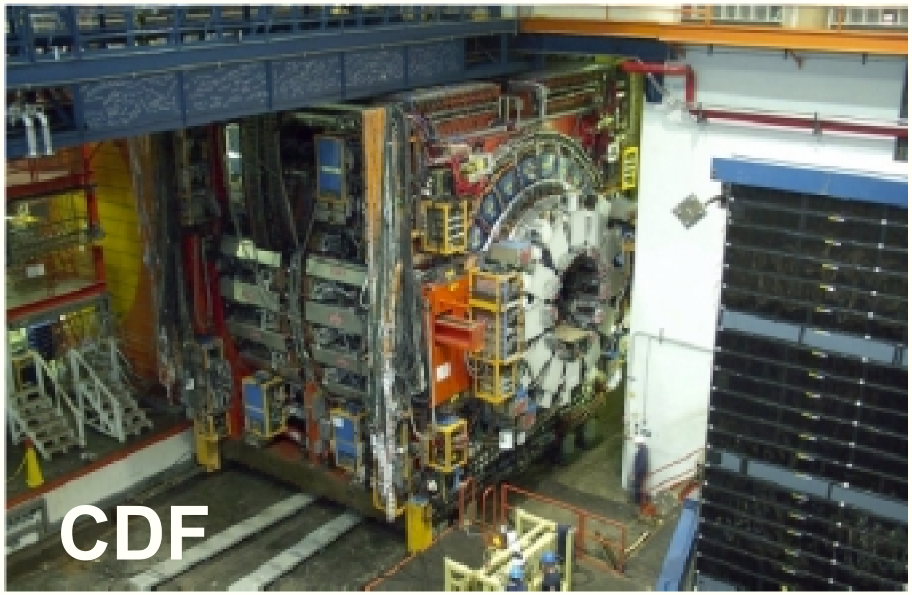


BaBar (Belle)

Next 5 years ~ 500 fb^{-1}

Precision measurement of sin2α, sin2β, as well as CKM elements….

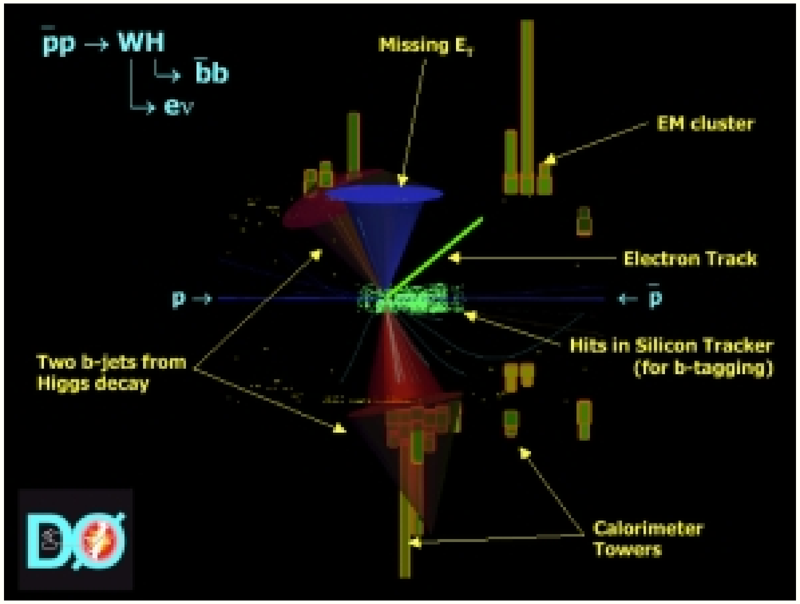


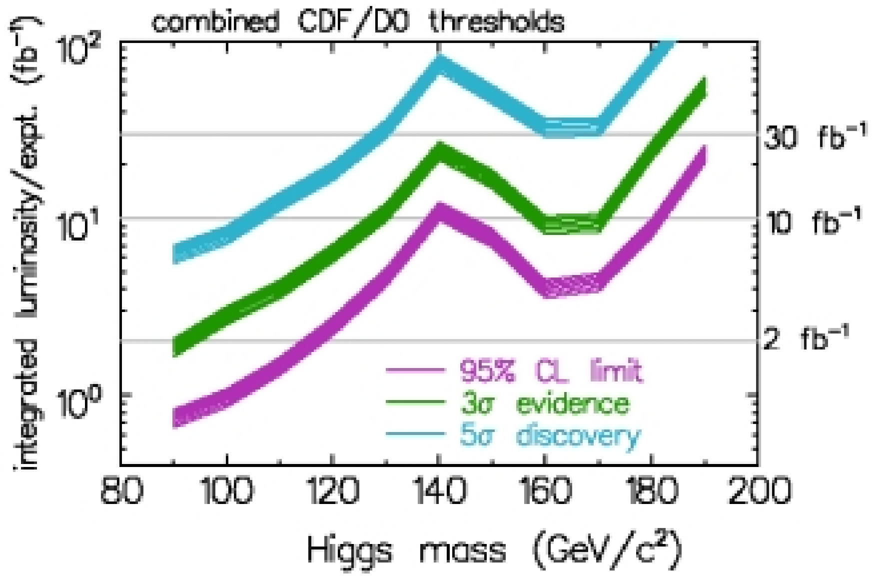


The Next Steps: What to Expect

Existing and Near-Term Program

Fermilab Run 2:
Pursuit of the Higgs



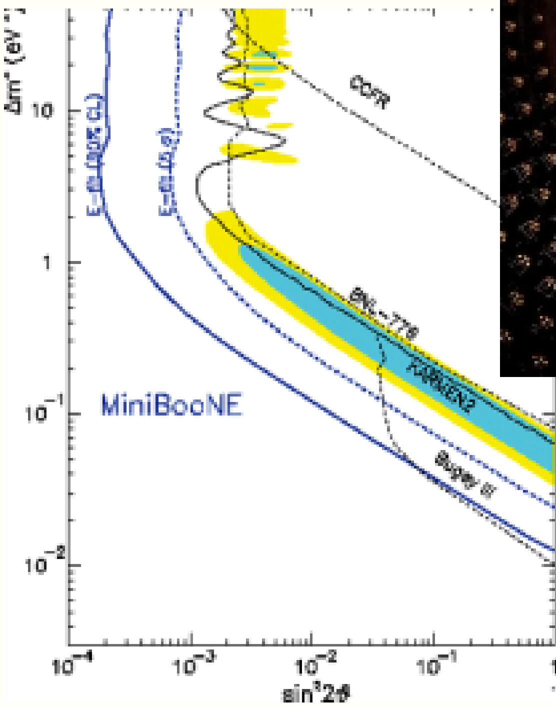


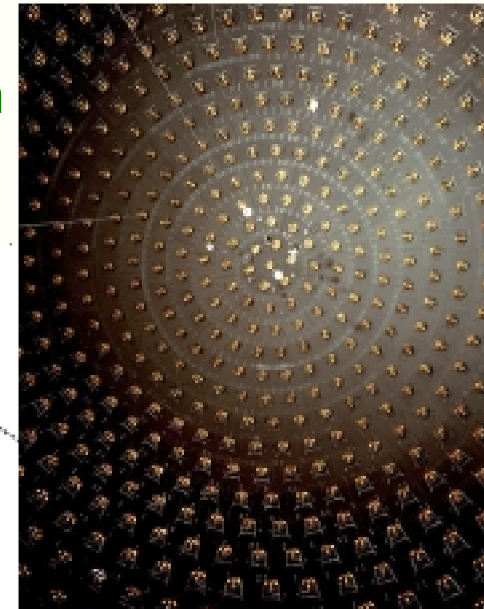
The Next Steps: What to Expect

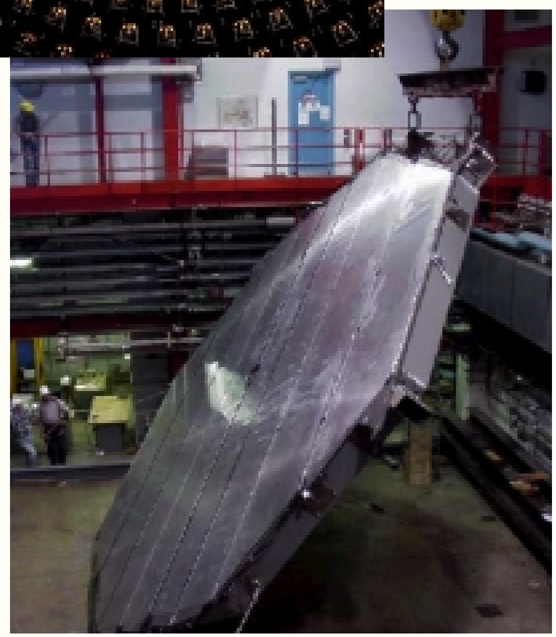
Existing and Near-Term Program

MiniBooNE

Refute or confirm LSND



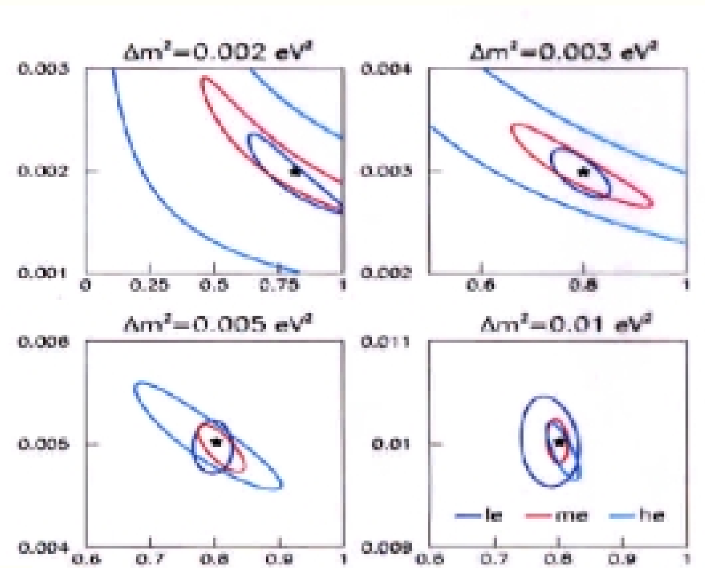




MINOS

(K2K, CERN–Gran Sasso)

Atmospheric ν parameters



Our First Recommendation

We recommend that the U.S. take steps to remain a world leader in the vital and exciting field of particle physics, through a broad program of research focused on the frontiers of matter, energy, space and time.

The U.S. has achieved its leadership position through the generous support of the American people. We renew and reaffirm our commitment to return full value for the considerable investment made by our fellow citizens. This includes, but is not limited to, sharing our intellectual insights through education and outreach, providing highly trained scientific and technical manpower to help drive the economy, and developing new technologies that foster the health, wealth and security of our nation and of society at large.

Who Are We?

The National Laboratories

- **Two large national laboratories – Fermilab and SLAC, plus ANL, BNL, Cornell, and LBNL.**
- **They provide major accelerator and detector facilities.**
- **They create intellectual hubs of activity.**
- **They provide much of the field,s technical infrastructure**
- **They enable the development of future accelerators and detectors.**

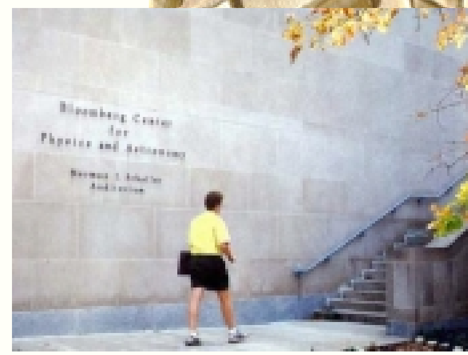
SLAC

Fermilab

In the future, the our national laboratories will continue to be at the center of particle physics.

Who Are We?

The Universities



- **HEP in the U.S. is built around a strong university-based community.**
- **University faculty, graduate students and postdocs make up more than 80% of the scientists in the field.**
- **University scientists provide training for our undergraduate and graduate students and renewal of the field.**
- **Many of the ideas and leadership in the field are based in the university community**

A healthy balance between universities and national laboratories is key to the success of the program we outline in this report.

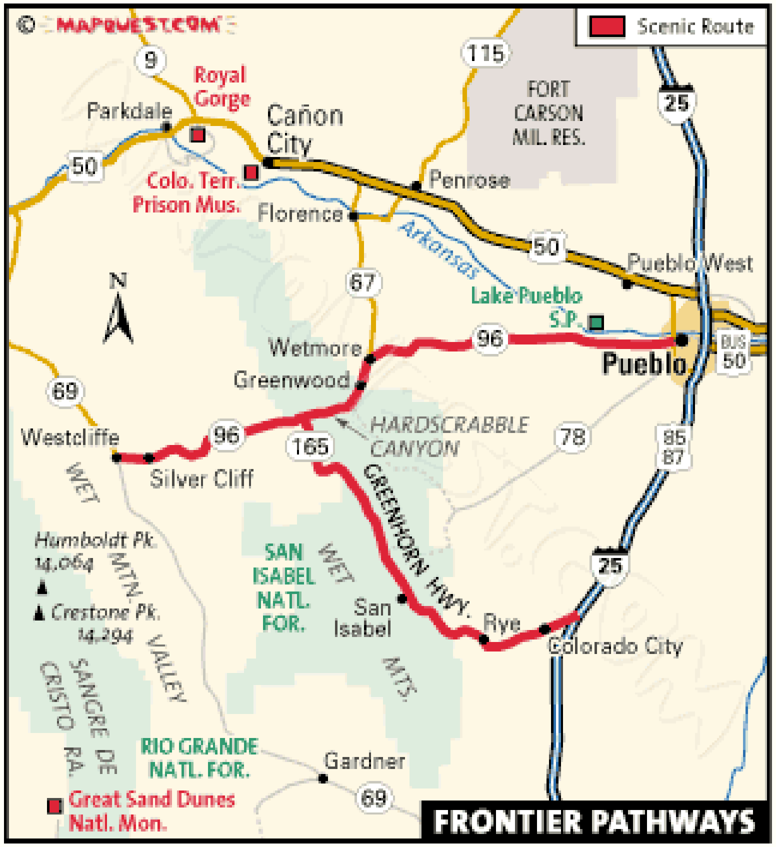
Developing a Long Range Strategy for HEP

A “roadmap” is an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field.

R. Galvin
Motorola

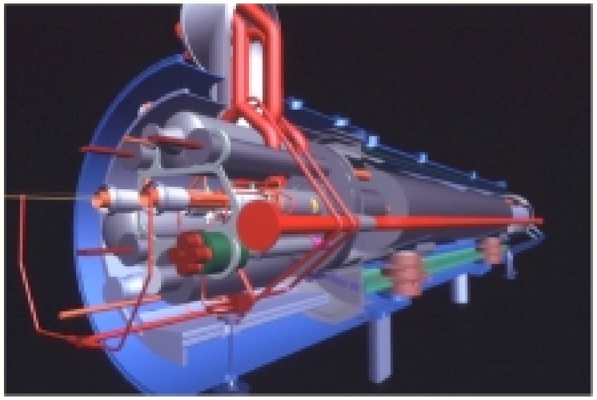
Frontier Pathway

Scenic and Historic Byway

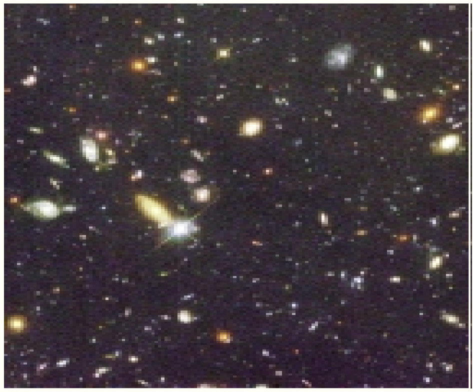


How Do We Do Particle Physics?

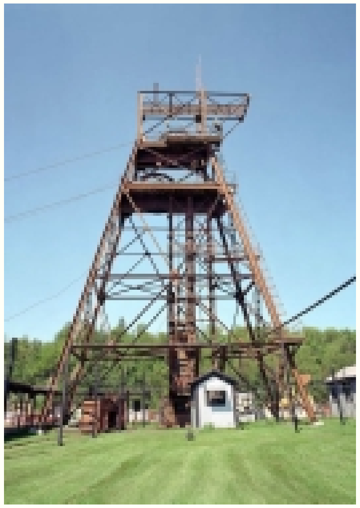
- We have many tools at our disposal from forefront accelerators to satellites in space to experiments deep underground.



Accelerator
LHC Magnet



Space



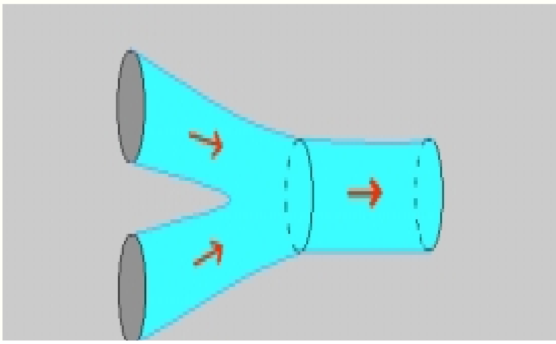
The Soudan Mine
MINOS

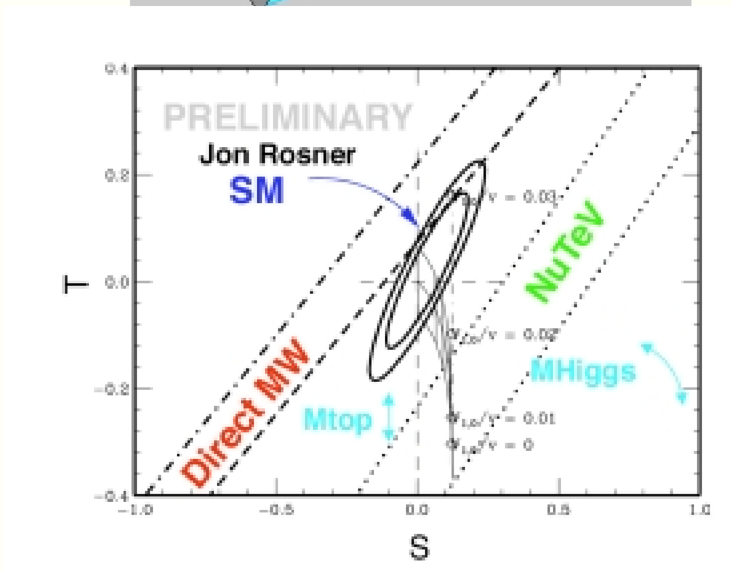
Our science requires forefront accelerators at the energy and luminosity frontiers. It also requires innovative experiments in space, underground, and away from accelerators.

Scientific Underpinnings of the Roadmap

Theoretical Physics and Phenomenology

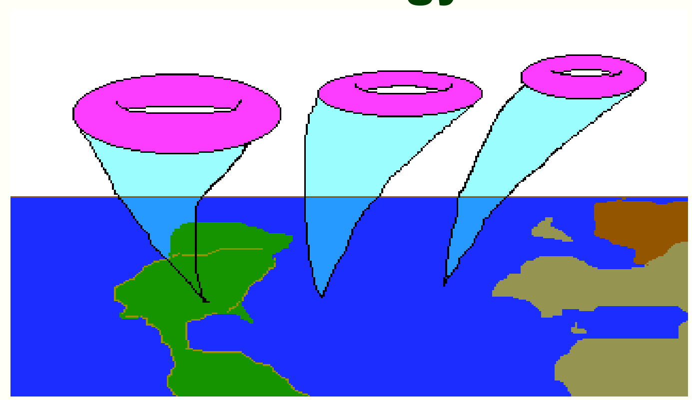
Bottom-up and top-down approaches…





- Higgs? Flavor?
- Supersymmetry?
- Extra Dimensions?

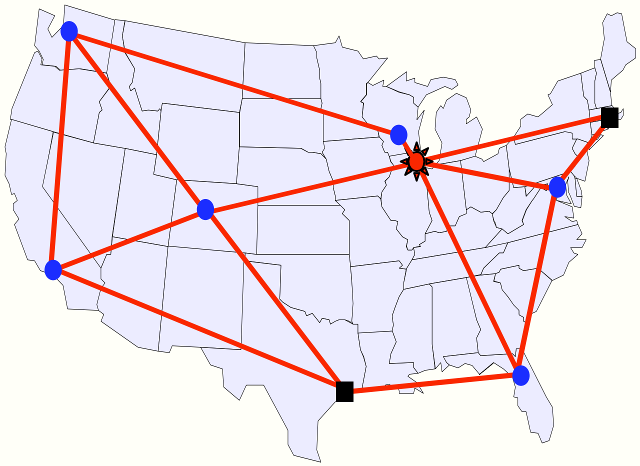
- String Theory
- Formal Theory
- Lattice Theory
- Phenomenology



Scientific Underpinnings of the Roadmap

Data Analysis

- **Extracting the science from complex modern detectors is extremely challenging.**
- **It requires the use of very sophisticated data analysis techniques**
  - **advanced statistical techniques,**
  - **detailed studies of systematic errors,**
  - **quantitative comparison with theoretical predictions.**
- **Developments in information technology, including data acquisition, processing, storage and networking are needed to service our distributed community.**



A transcontinental Data Grid composed of computational and storage resources of different types linked by high-speed networks.

Sufficient strength in data analysis capabilities must be developed to fully exploit the scientific potential of the roadmap.

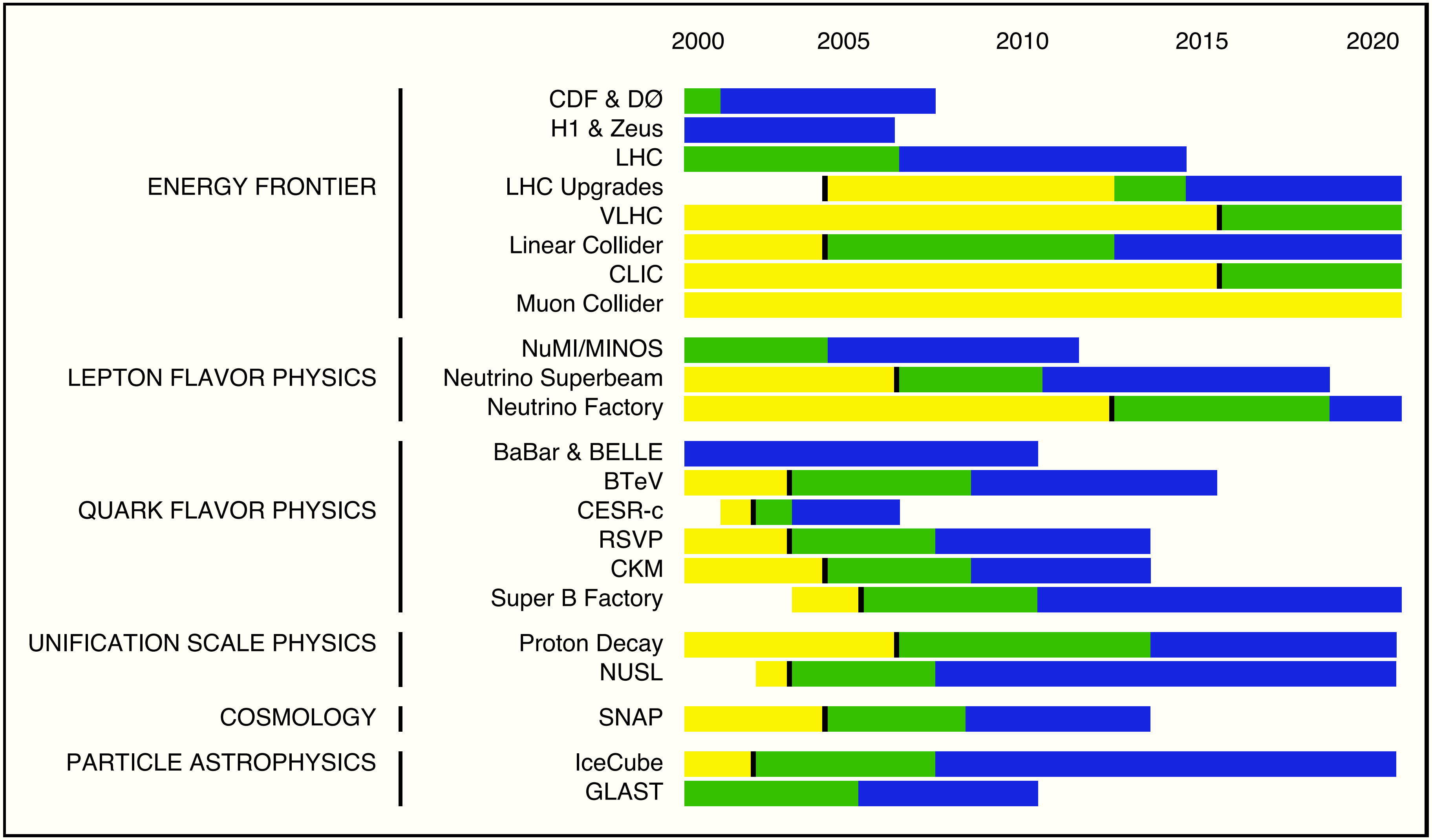
Strategic Steps Toward our Scientific Goals

A Multi-Prong Approach

- Elements of a Roadmap by Topic
  - The Existing and Near-Term Program
  - Theoretical Physics, Phenomenology and Data Analysis
  - The Energy Frontier
  - Lepton Flavor Physics
  - Quark Flavor Physics
  - Unification Scale Physics
  - Cosmology and Particle Physics
  - High-Energy Particle-Astrophysics

The roadmap lists the physics opportunities that we can see over the next twenty years. However, not all the avenues will be pursued, either in the U.S. or abroad. The roadmap provides the basis for the difficult choices that will have to be made.

The Particle Physics Roadmap

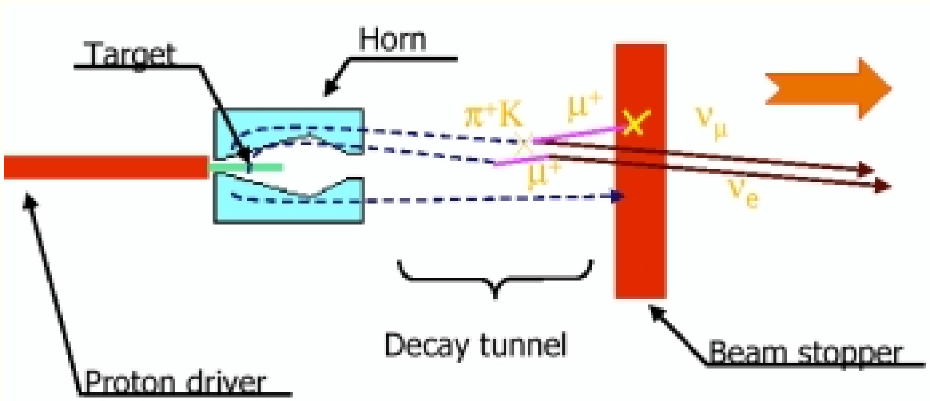


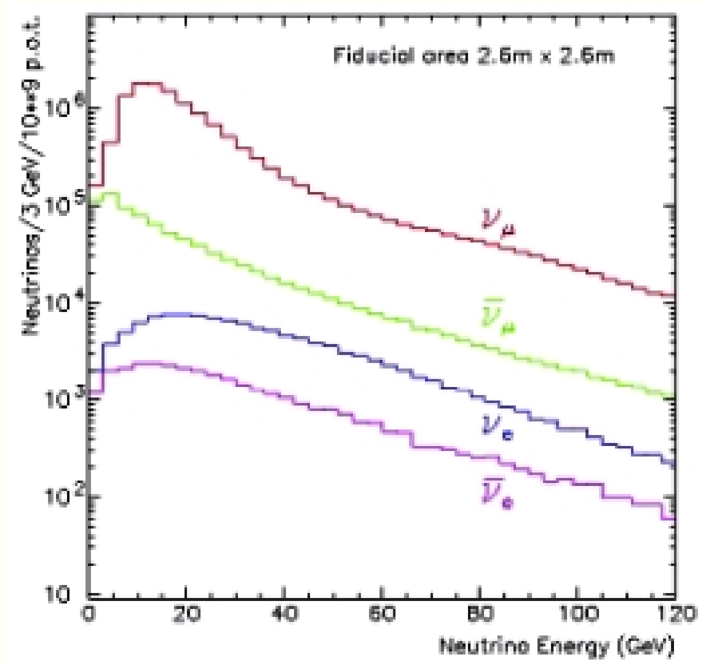
Lepton Flavor Physics

Neutrinos

Superbeam

Conventional Beam
Intense Proton Driver





Proton driver – 1 – 4 MW
Neutrino Energy – GeVs

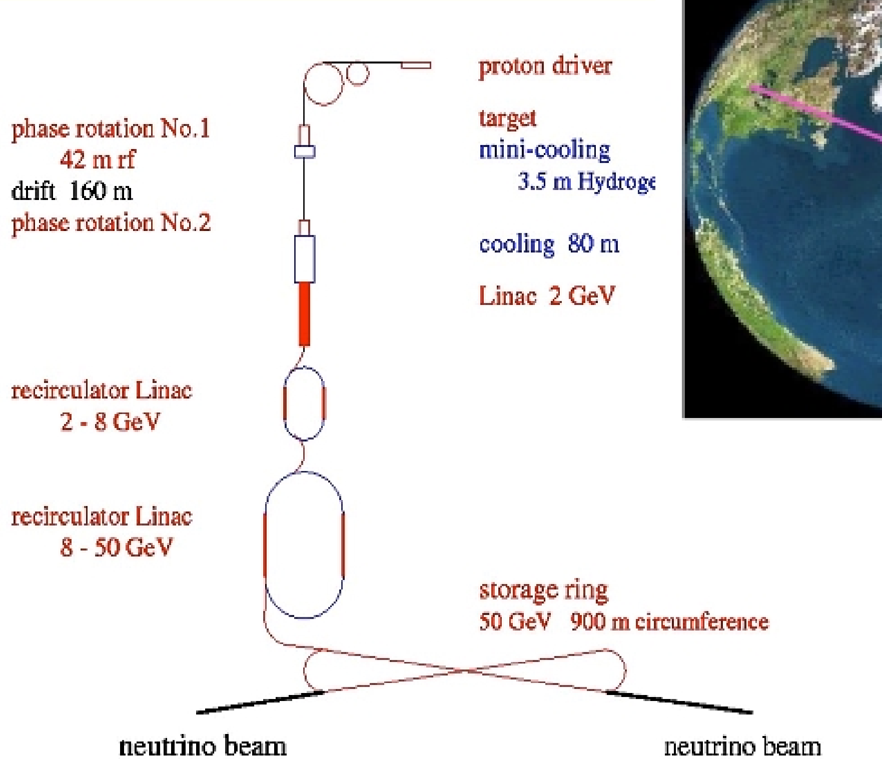
(optimum energy / detector distance ??)

- **Factor 10–100 beyond MINOS**
- **Accurate parameters**
  - **$s_{23} \sim 10^{-2}$, $s_{13} \sim 5 \times 10^{-3}$**
- **Poor sensitivity to δ**

Lepton Flavor Physics

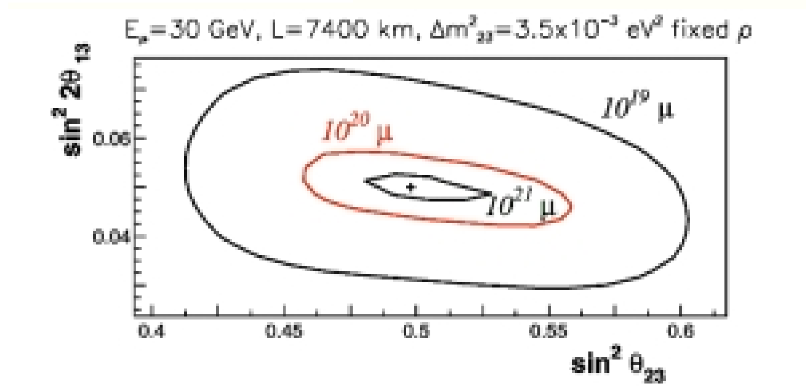
Neutrinos

Neutrino Factory
Muon Collider



Example:
7400 km baseline

Fermilab → Gran Sasso
"world project"

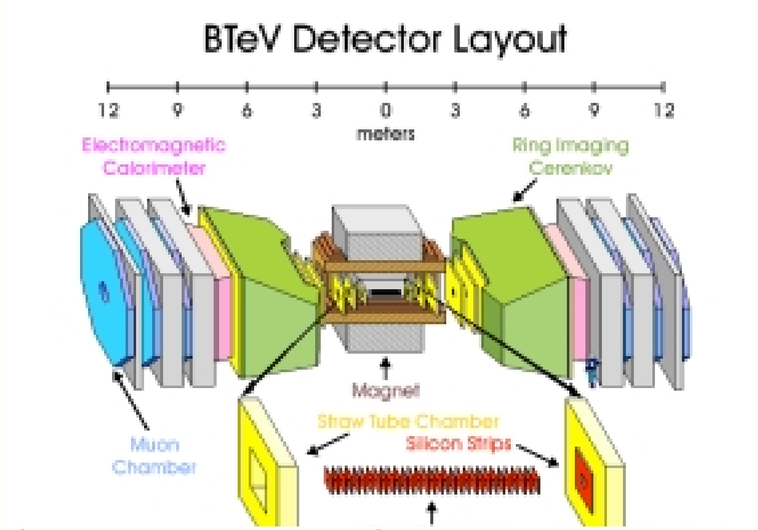


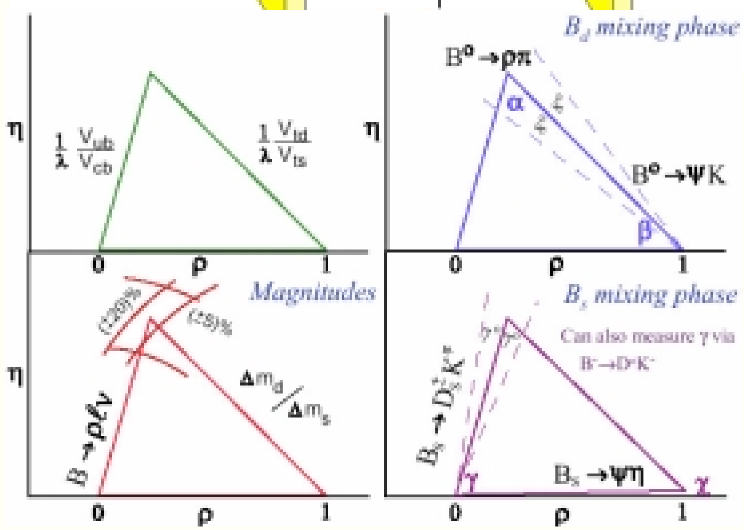
neutrino beams
select ν_μ,s or anti ν_μ,s

- **Accurately determine mixing matrix**
- **Measure CP violation in ν sector?**
  Depends on θ_{13}??

The Particle Physics Roadmap

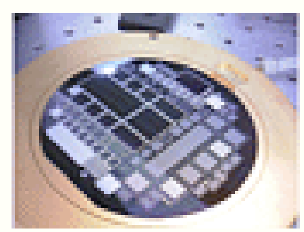
Quark Flavor Physics





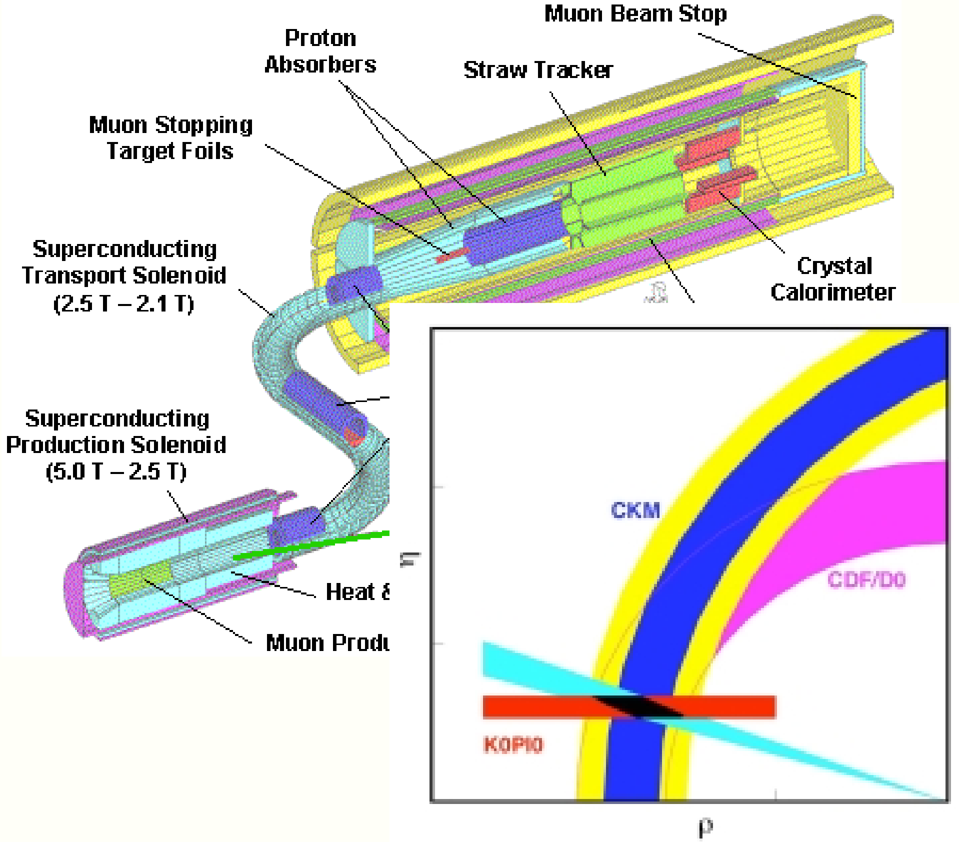
- **Quark mass, mixing, CP violation, using strange, charm and bottom hadrons….**

- **Precision measurements to challenge the Standard Model.**



CLEO-c, BTeV, SuperBaBar ….
(LHC-b)

The Particle Physics Roadmap

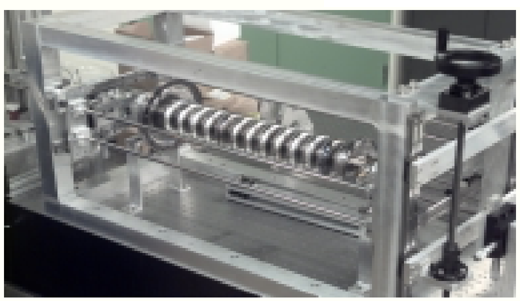


Very Rare Processes

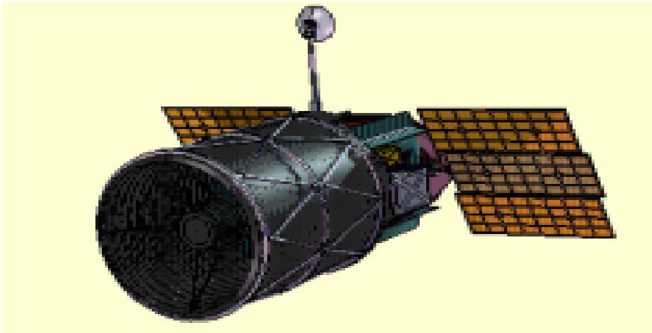
- Some very rare processes probe CP violation in the strange quark system.
- Lepton flavor violation and proton decay are consequences of grand unification!

$K^0 \rightarrow \pi^0 \nu\nu \qquad K^+ \rightarrow \pi^+ \nu\nu,$

$\mu \rightarrow e\,\gamma \qquad p \rightarrow K^+ \nu$

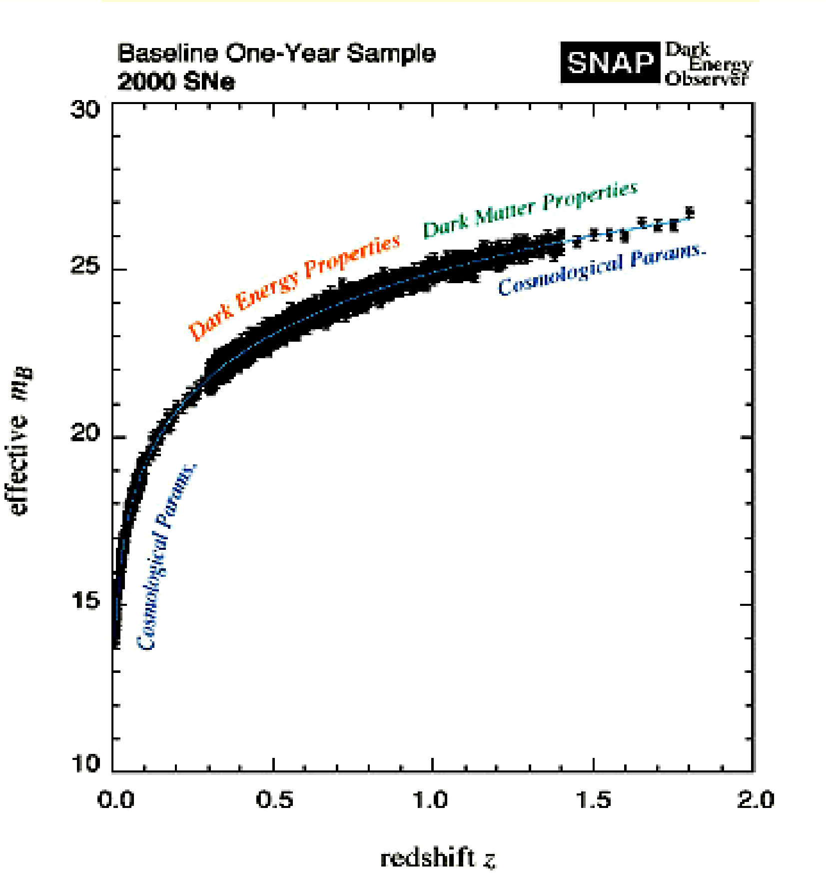


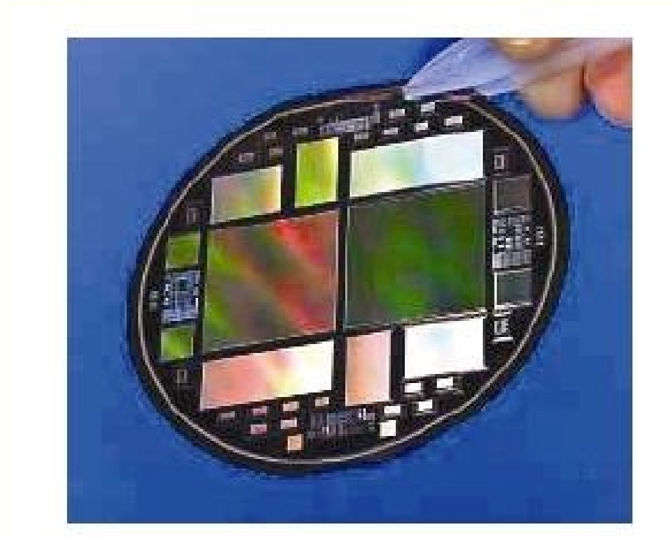
CKM, K0PI0, MECO, UNO …



Cosmology and Particle Physics

Dark Energy

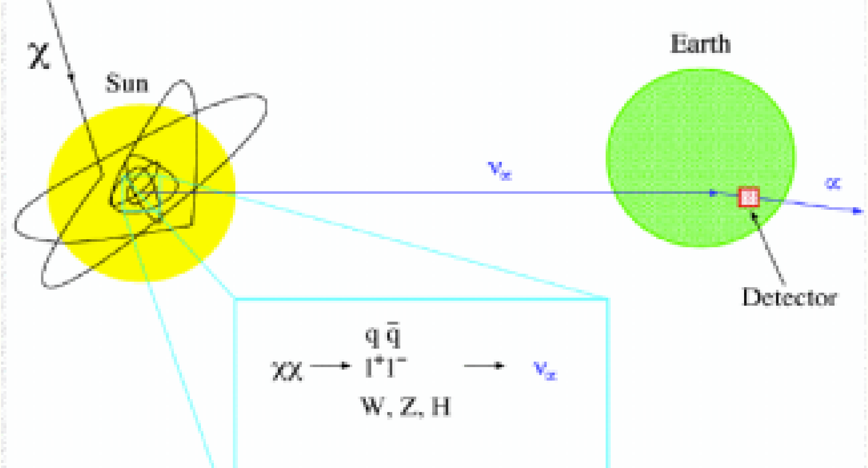




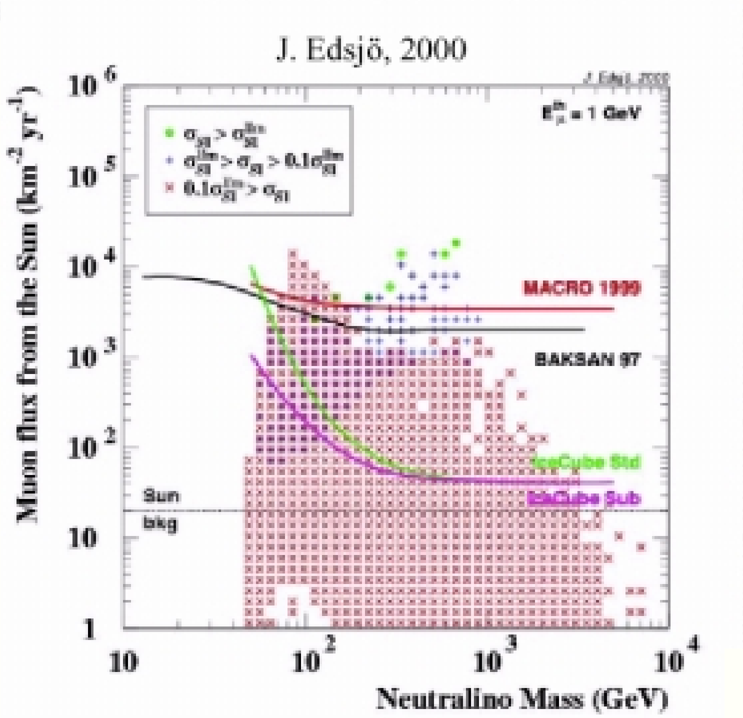
The SNAP Dark Energy Detector. SNAP requires R&D to develop a detector with one billion CCD,s.

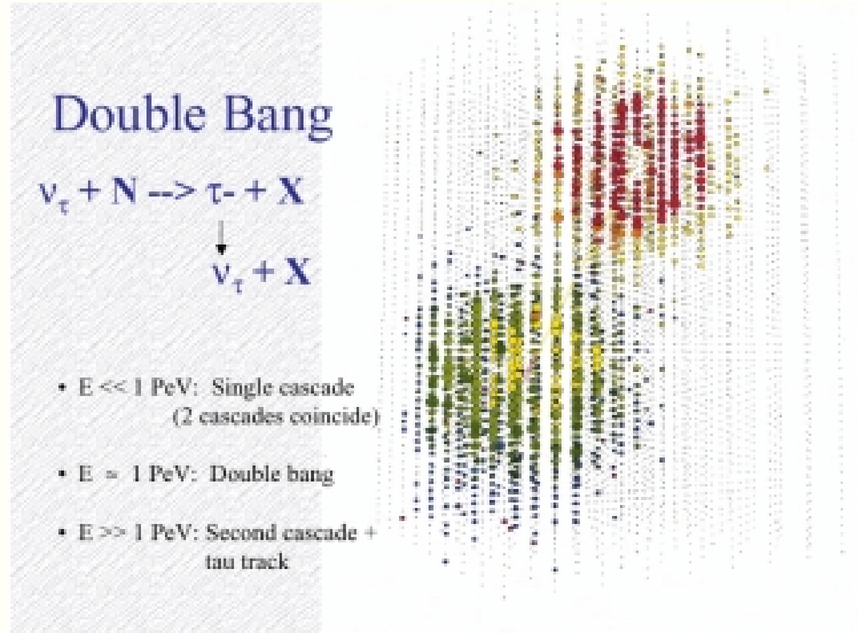
Particle Physics with IceCube

WIMP Annihilation in Sun



Sensitivity similar to Genius





Characteristic signature for ν_τ interactions

How Do We Propose to Make Choices?

Particle Physics Project Prioritization Panel (P5)

- **P5 will monitor, set priorities and make choices for midsized projects (~ $50M to $500M)**
- **Guidelines for P5**
  - P5 will be the guardian of the roadmap.
  - It should be a broad-based panel.
  - The members should be selected by a process similar to the selection of HEPAP subpanelists.
  - P5 should have some representation from the existing program committees.
  - It needs to have sufficient continuity of membership to develop and sustain a consistent program.
  - The panel should advise HEPAP and the agencies on the program.

Prioritization is central to our plan for a diverse, aggressive program of particle physics

Our Second Recommendation

We recommend a twenty-year roadmap for our field to chart our steps on the frontiers of matter, energy, space and time. The map will evolve with time to reflect new scientific opportunities, as well as developments within the international community. It will drive our choice of the next major facility and allow us to craft a balanced program to maximize scientific opportunity.

We recommend a new mechanism to update the roadmap and set priorities across the program. We understand that this will require hard choices to select which projects to begin and which to phase out. Factors that must be considered include the potential scientific payoff, cost and technical feasibility, balance and diversity, and the way any proposed new initiative fits into the global structure of the field.

What is the Next Big Step?

Exploration of the TeV Scale

- **This exploration requires the CERN LHC –**
  - **A proton-proton collider with an energy seven times that of the Tevatron.**

- **Together with a high-energy e+e- linear collider.**
  - **The LHC and a linear collider are both necessary to discover and understand the new physics at the TeV scale.**
  - **A coherent approach, exploiting the strengths of both machines, will maximize the scientific contributions of each.**

The centerpiece of our roadmap is the thorough exploration of the TeV scale.

Why a Linear Collider?

- **The linear collider accelerates electrons and positrons, structureless particles that interact through precisely calculable weak and electromagnetic interactions.**
- **A linear collider can:**
  - **Determine the spins and quantum numbers of new particles.**
  - **Measure cross sections and branching ratios.**
  - **Carry out precision measurements and expose crucial details of new physics.**

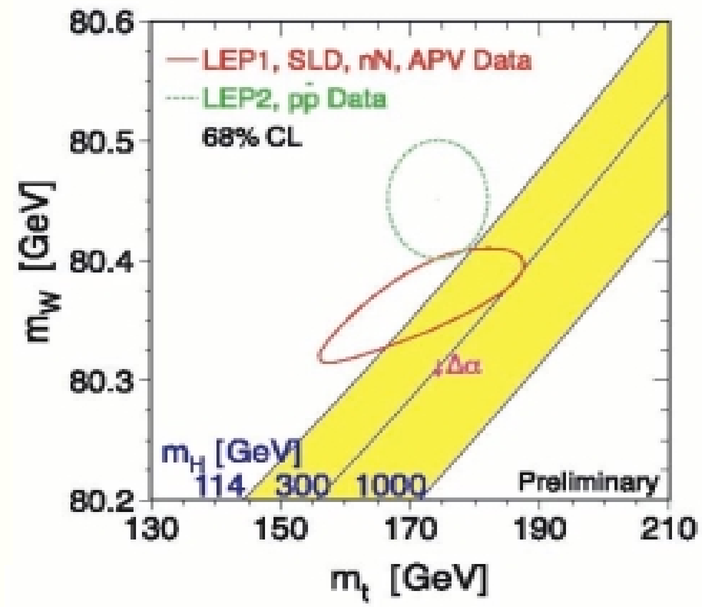
Physics program endorsed by the Asian and European Committees for Future Accelerators, by the U.S. high-energy physics community during the 2001 Snowmass workshop, and by this subpanel.

What Energy?

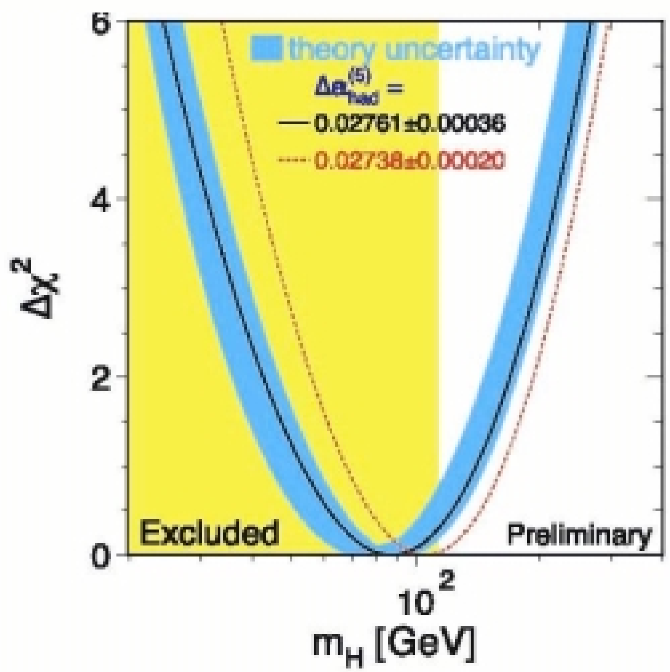
500 GeV: The First Step

- **The case for starting at 500 GeV builds on the success of the Standard Model.**
  - **We know there must be new physics, and precision data tell us where to look.**
- **The new physics is likely to include a Higgs.**
  - **The Higgs is a fundamental spin-zero particle – a new force, a radical departure from anything we have seen before.**

What Do We Know?
Standard Model Fit



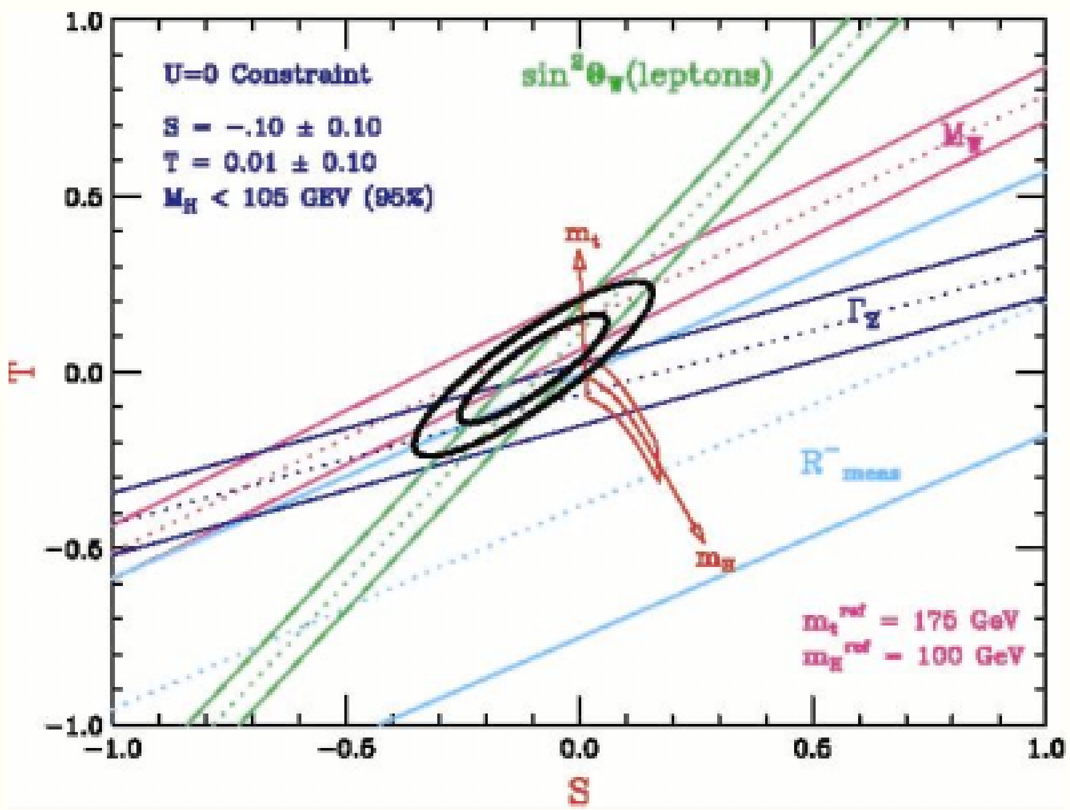
Fits to the Standard Model prefer a light Higgs boson, with a mass of less than 200 GeV.



Such a light Higgs boson is well within reach of a 500 GeV linear collider.

Why Both a Hadron and Electron Collider?

Precision Data



The present precision data were collected at hadron and electron machines.

The two probes provide complementary views – much like infrared and ultraviolet astronomy complement the optical.

We fully expect this theme to continue into the future.

How Will a 500 GeV Linear Collider Complement the LHC?

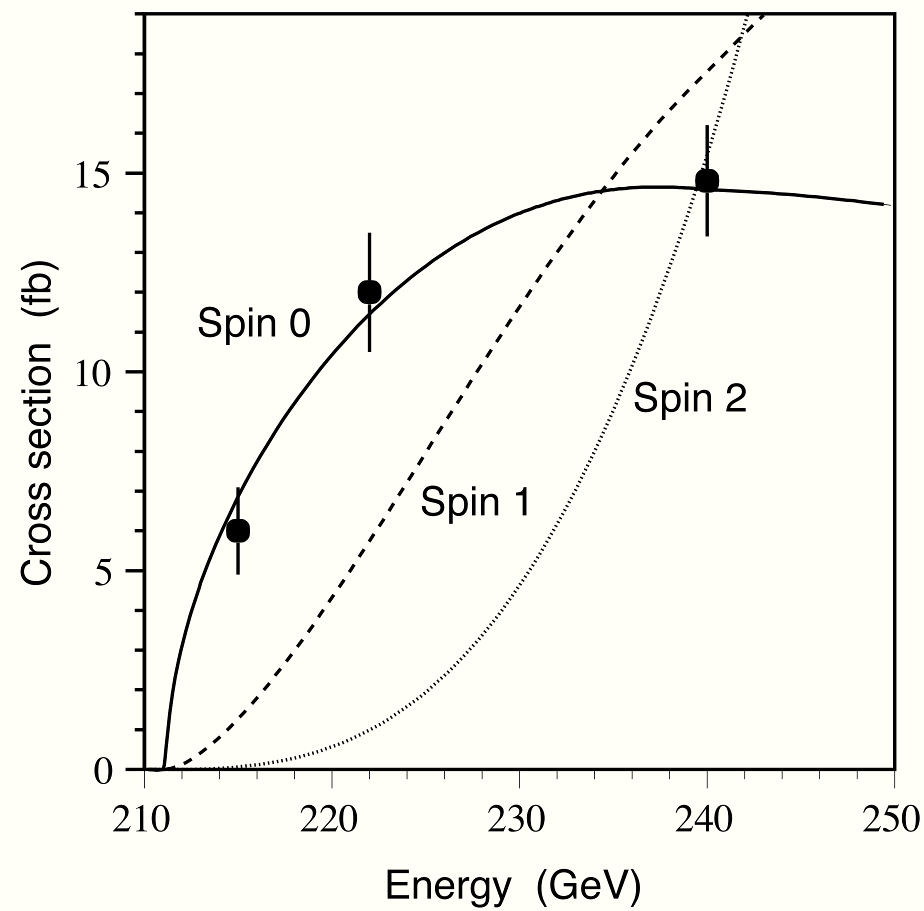
- **Experiments at the LHC are likely to discover the Higgs.**
- **But a linear collider answers crucial questions:**
  - **Does the Higgs have spin zero, as required?**
  - **Does it generate masses for the *W* and *Z*, and for the quarks and leptons?**
  - **Does the Higgs generate its own mass?**

The 500 GeV Linear Collider

Spin Measurement

The LHC can determine the spin of a Higgs if its decay into *ZZ* has sufficient rate. But the linear collider can measure the spin of any Higgs it can produce.

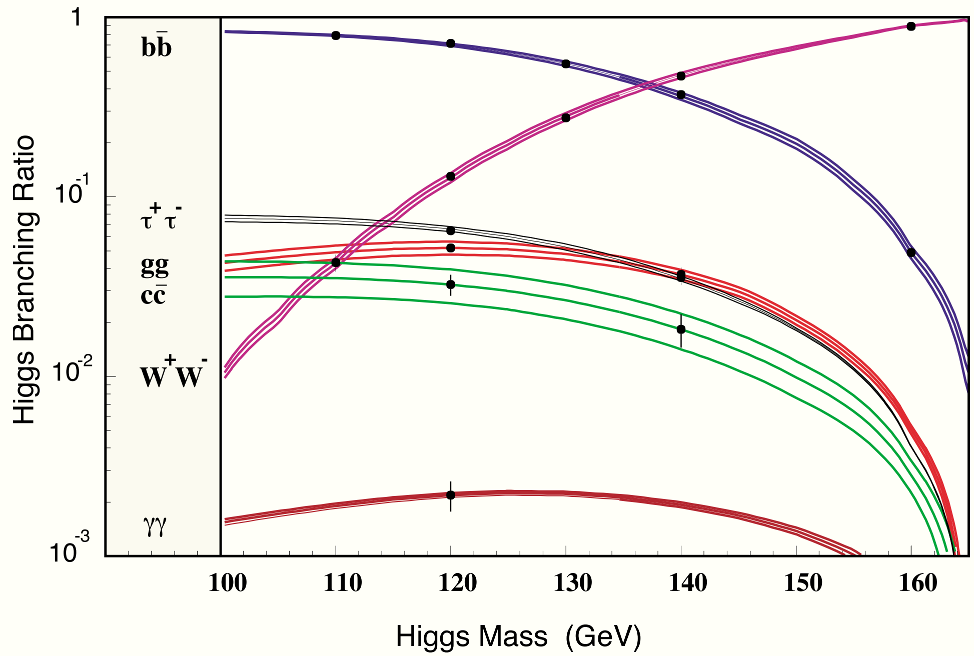
The process $e^+e^- \rightarrow HZ$ can be used to measure the spin of a Higgs particle.



The 500 GeV Linear Collider

Branching Fraction Measurement

The LHC will measure *ratios* of Higgs couplings. The linear collider, working with the LHC, can determine the *magnitudes* of these couplings very precisely.



The figure shows estimated measurements of the Higgs branching fractions, assuming a 120 GeV Higgs particle.

Why Is Higher Energy Important?

500 GeV → 800-1000 GeV

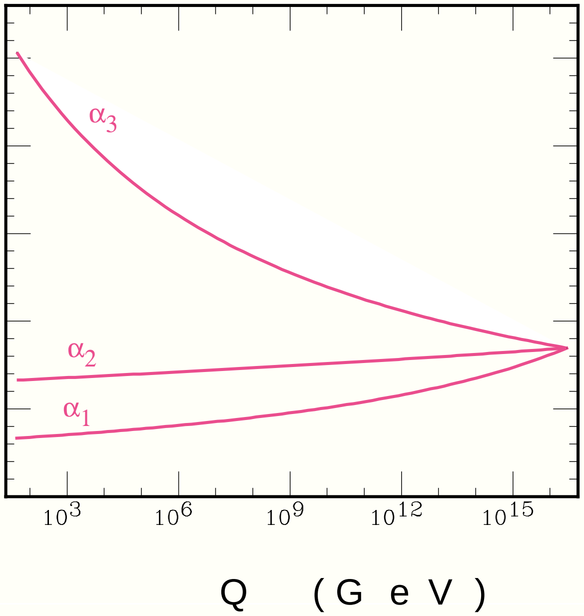
- At 500 GeV we expect to be able to study the Higgs.
- But our goals all point to other new physics at the TeV scale
  - Ultimate Unification
  - Hidden Dimensions
  - Cosmic Connections
- We have many ideas – but which, if any, is right?

Ultimate Unification

New Quantum Dimensions

- **There are already hints that quantum dimensions permit the electroweak force to unify with the strong nuclear force.**
  - **Protons are unstable and eventually decay.**

- **They give rise to supersymmetry, which unifies matter with forces.**
  - **Every known particle has a supersymmetric partner, waiting to be discovered at the TeV scale.**



Ultimate Unification

Testing Supersymmetry

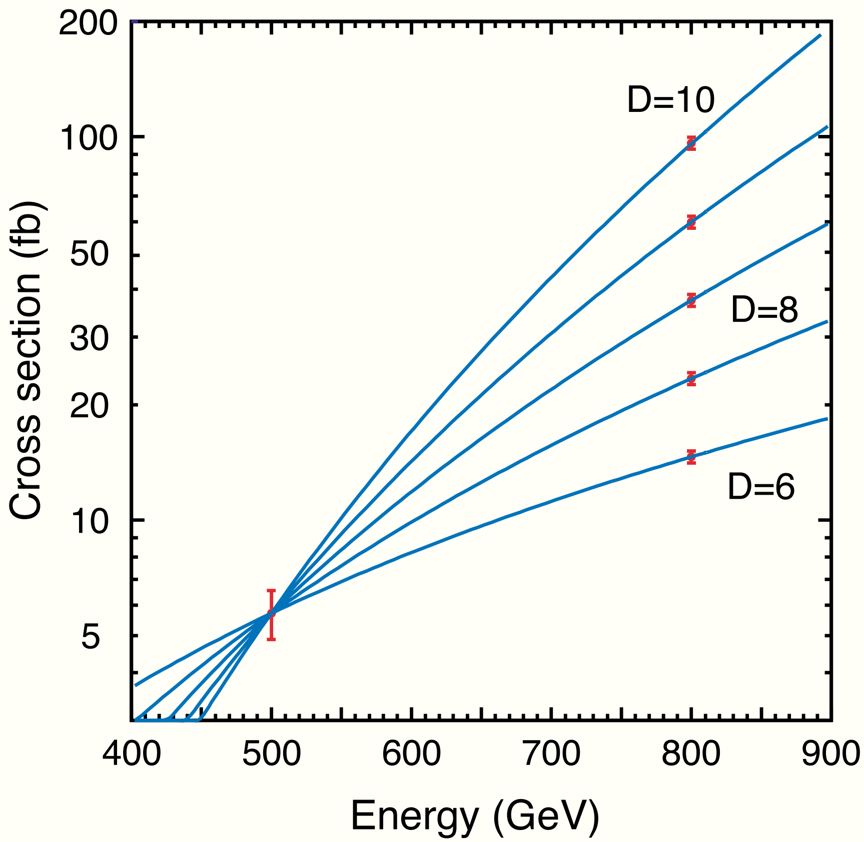
- **To test supersymmetry, we need to measure the superparticle spins and couplings. Do the spins differ by 1/2? Are the couplings correct?**
  - **All the superparticle masses and couplings can be precisely measured at a high-energy linear collider, provided they can be produced. Precision measurements are crucial.**
  - **Some superparticles should be in range of a 500 GeV machine; exploration of the full spectrum requires at least 800-1000 GeV.**

Revealing the DNA of matter…

Hidden Dimensions

New Spacetime Dimensions

- **Theories predict new hidden spatial dimensions.**
- **Particles moving in them induce new observable effects at the TeV scale.**
- **The LHC can find hidden dimensions; the linear collider can map their nature, shapes and sizes.**
  - **If gravitons travel extra dimensions, the linear collider can demonstrate that they have spin two.**
  - **Precision measurements at the linear collider can also detect for their indirect effects on TeV physics.**



Hidden Dimensions

Measuring The Number of Dimensions

New space-time dimensions can be mapped by studying the emission of gravitons into the extra dimensions, together with a photon or jets emitted into the normal dimensions.

The figure shows how measurements at different beam energies can determine the number and size of the extra dimensions.

From science fiction to science fact...

Cosmic Connections

Finding Dark Matter

- **What is the dark matter that pervades the universe?**
  - **Many models of TeV physics contain new particles that could make up the dark matter.**
  - **The dark matter might be neutralinos, stable neutral superparticles predicted by supersymmetry.**

- **Measurements at the linear collider will allow us to develop a predictive theory of this dark matter.**
  - **These measurements would push back our detailed knowledge of the early universe.**

The Inner Space / Outer Space Connection...

The Linear Collider

This Is Just The Beginning ….

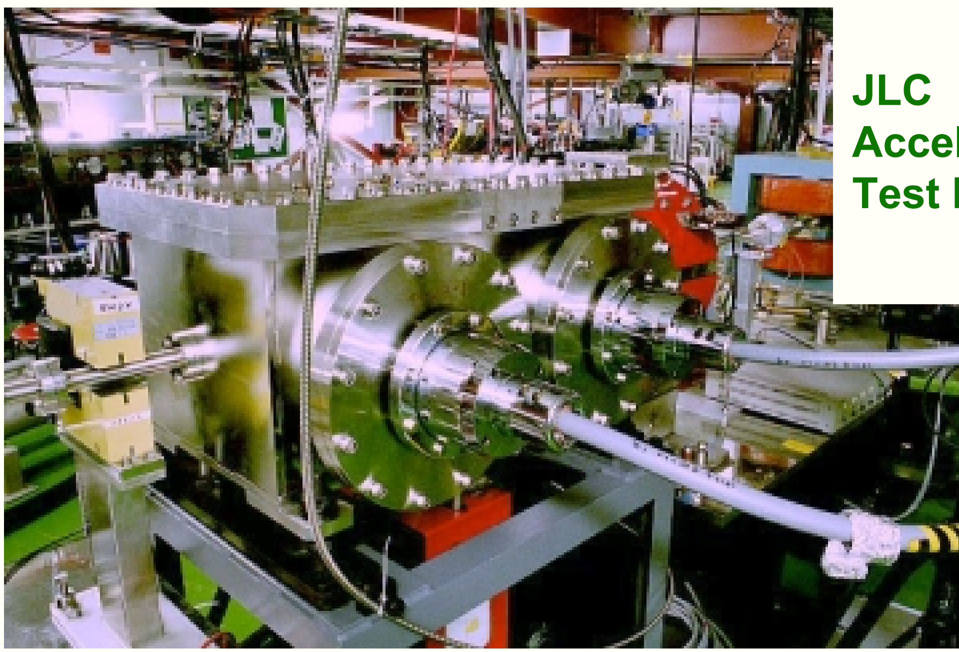
- The linear collider is a powerful instrument to probe the new physics at the TeV scale.
- Together with the LHC, it will reveal a world we can only begin to imagine.
- A high-luminosity linear collider, covering the energy range 500 to 800-1000 GeV, is crucially important to reach our goals.

We think the case is strong and that the mission is clear.

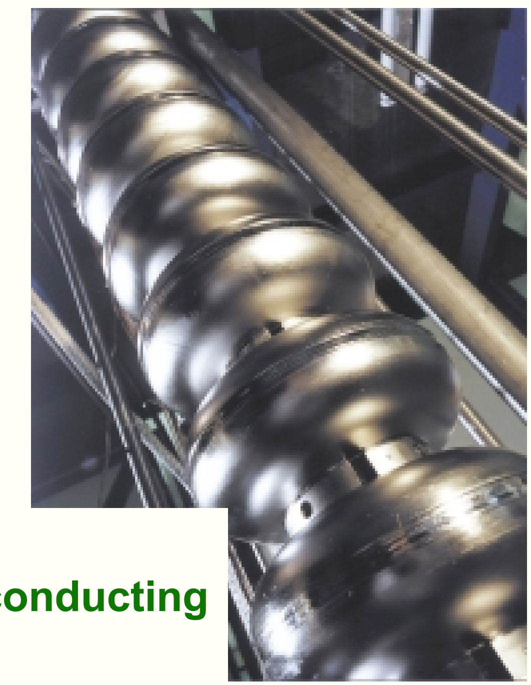
The Linear Collider
Technologies

NLC
High Power
Klystron

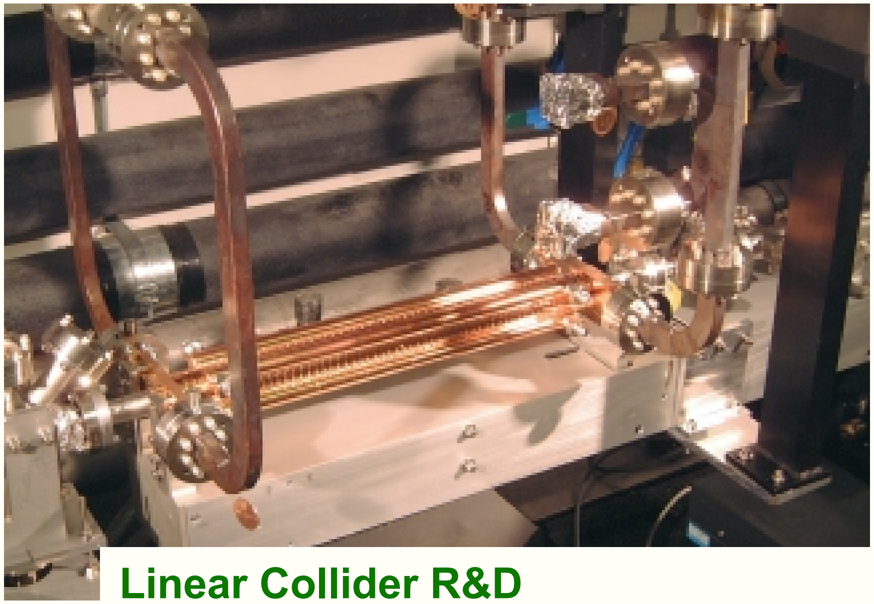
- The international accelerator community now firmly believes that a TeV-scale linear collider can be successfully built at an acceptable cost with the correct science-driven capabilities.
- This is a result of an intensive R&D period, where there has been a strong level of international cooperation and communication.



JLC
Accelerator
Test Facility



TESLA
Superconducting
Cavity



Linear Collider R&D
Test accelerating structures at SLAC

The Linear Collider
R&D Programs

- **R&D Program Status**
  - There are now at least two technologies that could be used.
  - Strong international collaborations have been established.

- **The Future R&D Program**
  - Further R&D is still needed, mostly in the areas of the RF systems, luminosity performance, and systems engineering, to reduce costs, reduce risks, and confirm the ultimate energy and luminosity reach of the machines.

Organizing the U.S. Linear Collider Effort

Forming a Linear Collider Steering Committee

- **The formation of an international organization under scientific leadership is necessary to complete the linear collider design and to initiate the collaborations for its physics use.**
- **As a first step, we recommend formation of a U.S. Linear Collider Steering Committee. It will**
  - **Coordinate and speak for the U.S. linear collider effort**
  - **Develop a plan toward a technical choice and design**
  - **Work with international partners on an international structure**
  - **Analyze options for U.S. hosted linear collider.**
- **The Steering Committee should**
  - **Include representatives from the laboratory and university communities**
  - **Mix management, accelerator, detector and scientific expertise**
  - **Report regularly to HEPAP.**

Our Third Recommendation

We recommend that the highest priority of the U.S. program be a high-energy, high-luminosity, electron-positron linear collider, wherever it is built in the world. This facility is the next major step in the field and should be designed, built and operated as a fully international effort.

We also recommend that the U.S. take a leadership position in forming the international collaboration needed to develop a final design, build and operate this machine. The U.S. participation should be undertaken as a partnership between DOE and NSF, with the full involvement of the entire particle physics community. We urge the immediate creation of a steering group to coordinate all U.S. efforts toward a linear collider.

The Linear Collider

Why Should We Bid to Host It in the U.S.?

- **The linear collider promises to be one of the greatest scientific projects of our time.**
  - **It will be at the frontier of basic science, of advanced technological development, of international cooperation, and of educational innovation.**
  - **It will attract many of the top scientists in the world to participate in the scientific and technical opportunities it offers.**

We believe that hosting the linear collider is a rare opportunity, and one that should be seized by the U.S.

The Linear Collider

Why Should We Bid to Host It in the U.S.?

- **A healthy worldwide physics program requires a distribution of major facilities around the globe.**
- **Past investments in accelerator facilities have enormously enriched our society.**
- **Locating such a facility in the U.S. would allow a greater portion of our economic investment to be recaptured through jobs and technological benefits.**

The Linear Collider

Is There a Model to Host It?

- If the linear collider is sited in the United States, we propose financing the $5-7B facility by a combination of investments
  - International investment is essential for a project of this scale.
  - A significant fraction of the linear collider must be financed by redirection of the existing U.S. high-energy physics program.
  - We believe that a bold new initiative like the linear collider merits new funding from the U.S. government.
- We envision that the host country, in this case the U.S., would contribute about two-thirds of the cost of the project, including redirection.

Our Fourth Recommendation

We recommend that the U.S. prepare to bid to host the linear collider, in a facility that is international from the inception, with a broad mandate in fundamental physics research and accelerator development. We believe that the intellectual, educational, and societal benefits make this a wise investment of our nation's resources.

We envision financing the linear collider through a combination of international partnerships, use of existing resources, and incremental project support. If it is built in the U.S., the linear collider should be sited to take full advantage of the resources and infrastructure available at SLAC and Fermilab.

Investing in the Future of the Field

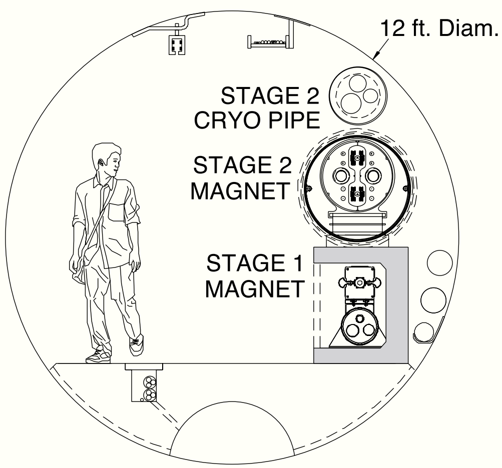
Accelerator R&D

- **Advances in particle physics depend critically on developing more powerful particle accelerators.**
- **It is imperative for the U.S. to participate broadly in the global accelerator R&D program.**
- **Accelerator R&D has important impacts elsewhere in science and technology.**

We give high priority to accelerator R&D because it is absolutely critical to the future of our field.

Accelerator R&D

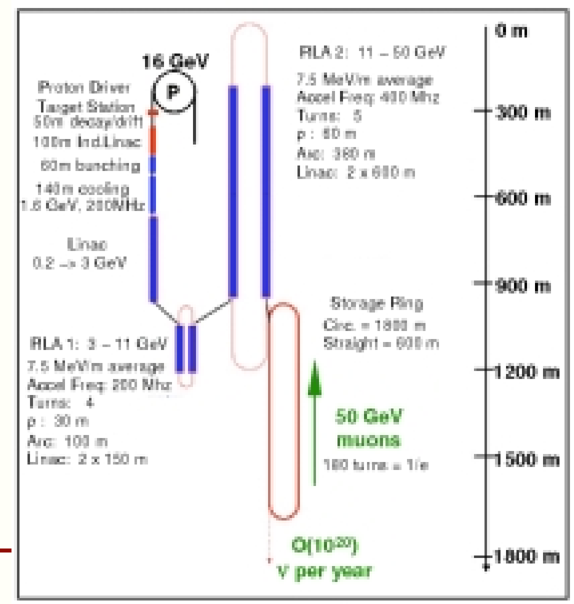
Very Large Hadron Collider



- High-field magnet research is particularly important.
- An international collaboration should be formed as early as possible.
- We strongly support R&D toward such a machine at about the current level of effort.

Neutrino Factory

- We recommend continued R&D near the present level.
- The level of effort is well below what is required to make an aggressive attack toward a neutrino factory.
- International collaboration on the essential muon cooling experiment is very important.



Our Fifth Recommendation

We recommend that vigorous long-term R&D aimed toward future high-energy accelerators be carried out at high priority within our program. It is also important to continue our development of particle detectors and information technology. These investments are valuable for their broader benefits and crucial to the long-range future of our field.

HEPAP Subpanel

Summary

- The past few years have been very productive. They have defined an exciting future for the field.
- The near-term program at PEP-II, at the Tevatron and for long baseline neutrinos provides a solid foundation on which to build.
- The LHC is crucial to the long-term program; it must be strongly supported.
- We believe that a companion linear collider offers the future for which we should strive. We urge that the U.S. prepare to bid to host the facility.
- This should all be done within the context of a broad and responsible program addressing our ultimate physics goals.